

Exploration Spacecraft and Space Suit Internal Atmosphere Pressure and Composition

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Image: NASA/JPL/Combi/MSS

Historical Cabin and Space Suit Atmospheres



Program	Cabin Pressure, kPa (psia)	Cabin Oxygen Concentration, volume %	EVA Suit Pressure, ⁽¹⁾ kPa (psia)	EVA O ₂ Pre-breathe Time, minutes	EVA Prebreathe Conditions
Mercury	34.5 (5)	100	-	-	-
Gemini/Apollo	34.5 (5)	100	25.8 (3.75)	0	-
Skylab	34.5 (5)	70	25.8 (3.75)	0	-
Shuttle	70.3 (10.2)	26.5	29.6 (4.3)	40	In-suit (after 36 hours at 70.3 kPa)
	101.3 (14.7)	21	29.6 (4.3)	240 ⁽³⁾	In-suit
ISS/US	101.3 (14.7)	21	29.6 (4.3)	120-140	Mask and in-suit; staged w/exercise
				240 ⁽³⁾	In-suit
Salyut, Mir, ISS/Russian	101.3 (14.7)	21	39.2 (5.7) ⁽²⁾	30	In-suit

References: Carson, et al. (1975), McBarron, et al. (1993), Waligora, et al. (1993), NASA (2002), NASA (2003).

(1) 100% oxygen.

(2) Can be reduced to 26.5 kPa (3.8 psia) for short-duration work regime.

(3) Under emergency conditions, a minimum of 150 minutes of unbroken prebreathe is recommended.

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What Drives Cabin Atmosphere Selection?

▪ Crew Health and Safety Requirements

- Crew Physiology
- Decompression Sickness Prevention
- Emergency EVA Capability
- Rapid Cabin Decompression Response

▪ Materials Requirements

- Materials Flammability
- Materials Off-gassing

▪ Science Requirements

- Microgravity and Partial-Gravity Physiology Studies

▪ Program Requirements

- Mission Segments and Durations
- EVA Frequency
- Cross-Vehicle Atmosphere Compatibility

▪ Mission/Vehicle/Space Suit Optimization

- Structure, Equipment, and Consumable Mass
- Thermal Control Power Requirements
- Space Suit Mobility and Glove Dexterity
- Crew Time
- Crew Comfort and Performance
- Cost

→ indicates issues addressed in this presentation

*Verification
of equipment
function*

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Bioastronautics Roadmap Content: Barophysiology Research Requirements

20p	What is the most effective pre-EVA Decompression Sickness (DCS) prevention strategy to include pre-breathe with various gases, exercise and other medical measures?
20q	What are the appropriate screening procedures to minimize predispositions for DCS?
20r	What are the resources and techniques for early diagnosis of DCS signs and symptoms, including the use of Doppler U/S and other bubble detection technologies?
20s	What are the best methods for predicting DCS risk and for reducing the risk, based on understanding of the physiological mechanism for bubble formation and propagation, employing best available knowledge from flight and analog environment experience?
20t	What are the most effective yet safe, and energy- and space-efficient means of managing DCS in the spaceflight milieu, including the use of hyperbaric oxygen delivery and other promising technology, and how might they be adapted for reduced-G operations?
20u	What is the actual risk of space-related DCS? (de novo physiological causes and acute environmental insult - e.g., leaking module or damaged EMU etc.)
20v	What are the operational and medical impacts of off-nominal performance of DCS countermeasures?
20w	What are the risk factors that can increase the likelihood of DCS, such as the presence of Patent Foramen Ovale (PFO)?
20x	What is the likelihood of surviving an acute environmental insult severe enough to cause damage to the vehicle or spacesuit?
20y	Is it possible and what are the DCS risk mitigation options for interplanetary EVA (e.g., moon and Mars) given that a tri-gas breathing mixture including argon is present?
20z	What is the role of individual susceptibility, age and gender on the risk of DCS during NASA operations involving decompression?
20aa	What are the available and new technologies needed to provide hyperbaric treatment options on the ISS and future habitats (or vehicles) beyond LEO (e.g., on the moon or Mars)?
20ab	What is the correlation between the detection/existence of gas phase creation in the bloodstream and development of clinically significant DCS?

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Bioastronautics Roadmap Content: Life Support and Habitation Research Requirements

EVA

	What EVA system design and minimum prebreathe protocol can be developed to reduce the risk of decompression sickness?
39a	
39b	What suit and PLSS technology must be developed to meet mission requirements for EVA mobility?
39f	How do we improve glove dexterity?
39k	What biomedical sensors are needed to enhance safety and performance during EVAs?

Air Revitalization

41a	What new developments are needed to meet all the requirements for controlling trace contaminants, atmospheric pressure, O ₂ and CO ₂ partial pressure?
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Thermal Control

42b	What materials and designs will meet the heat acquisition (cold plates, heat exchangers, cooling jackets, etc.) requirements for specified missions?
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Biomass Production

44a	What are the optimal methods of plant growth for a specified mission, including development of appropriate hardware, management of light, water, nutrients, gas composition and pressure, trace contaminants, horticultural procedures and disease risks?
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Food

40h	What are the impacts of reduced Gravity and atmospheric pressure on the food processing activities?
40i	What are the impacts of reduced Gravity and atmospheric pressure on the food preparation activities?

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Physiological Requirements (NASA (1995))

- Provide sufficient total pressure to prevent vaporization of body fluids (> 6 kPa (0.9 psia)).
- Provide sufficient oxygen partial pressure for adequate respiration.
 - Determined by partial pressure of oxygen in the alveoli of the lung.
 - Oxygen partial pressure must not be so great as to induce oxygen toxicity.
- Provide a physiologically inert gas for long durations (in excess of two weeks) to prevent atelectasis.
 - Absorption Atelectasis: collapse of obstructed alveoli due to complete gas absorption (see West (1990)).

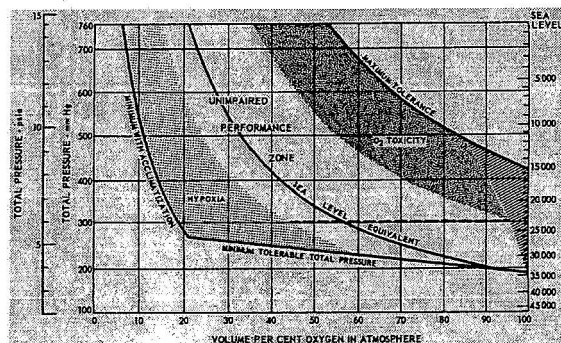


Figure: Webb (1964) (also NASA (1995)).

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Alveolar Gas Equation

- Relates ambient atmosphere conditions to oxygen partial pressure in the alveoli, the site of oxygen transfer to the blood.
- General form derived from molar balance on alveolar air exchange:

$$P_{AO2} = \frac{P_{IO2}[RQ(P - P_{AH2O}) + P_{ACO2}(1 - RQ)] + P_{ICO2}(P - P_{AH2O}) - P_{ACO2}(P - P_{IH2O})}{RQ(P - P_{IH2O}) + P_{ICO2}(1 - RQ)}$$

- Simplified form commonly found in physiology textbooks (assumes no carbon dioxide in inspired air, $P_{ICO2} = 0$):

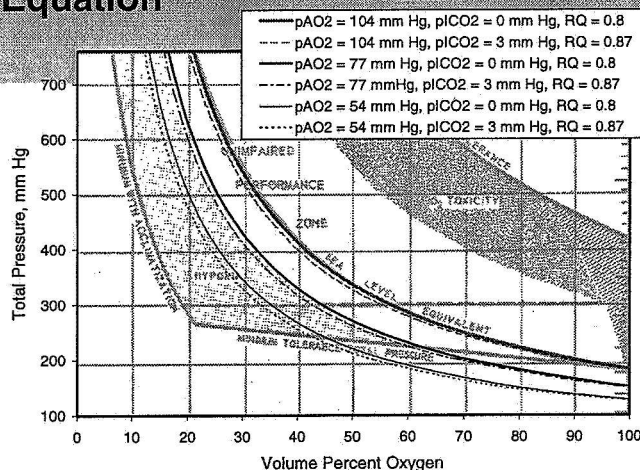
$$P_{AO2} = F_{IO2}(P - P_{AH2O}) - P_{ACO2}\left(F_{IO2} + \frac{1 - F_{IO2}}{RQ}\right)$$

P	= total (barometric) pressure
P_{IO2}	= inspiratory (ambient) O_2 partial pressure
P_{IH2O}	= inspiratory (ambient) H_2O partial pressure
P_{ICO2}	= inspiratory (ambient) CO_2 partial pressure
F_{IO2}	= inspiratory (ambient) O_2 fraction (dry)
	= $P_{IO2}/(P - P_{IH2O})$

P_{AO2}	= alveolar O_2 partial pressure
P_{AH2O}	= alveolar H_2O partial pressure
P_{ACO2}	= alveolar CO_2 partial pressure
RQ	= respiratory quotient (molar ratio of CO_2 production to O_2 consumption)

Alveolar Gas Equation Predictions

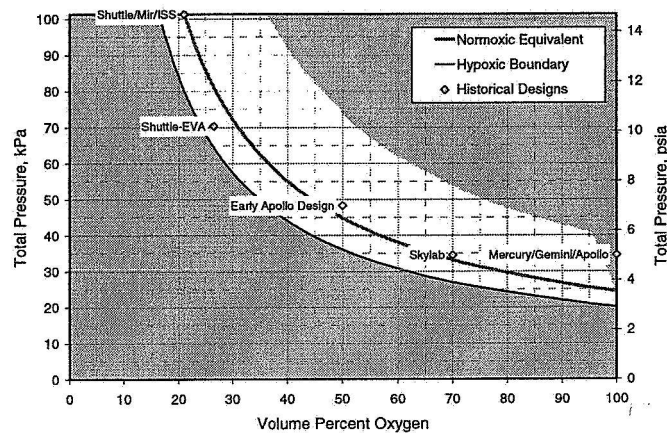
Alveolar Oxygen Partial Pressure	Approximate Equivalent Altitude	
mm Hg	ft	m
104	0	0
77	6000	1830
54	12000	3660



Results shown for "textbook" conditions ($p_{ICO2} = 0$ mm Hg, $RQ = 0.8$) and expected "advanced life support" conditions ($p_{ICO2} = 3$ mm Hg, $RQ = 0.87$).
Other Assumptions: $p_{IH2O} = 9.2$ mm Hg, $p_{AH2O} = 47$ mm Hg, $p_{ACO2} = 40, 34,$ and 32 mm Hg for $p_{AO2} = 104, 77,$ and 54 mm Hg, respectively.

Physiological Bounds

- Normoxic equivalent corresponds to sea-level alveolar pAO₂ of 13.9 kPa (104 mm Hg or 2.0 psia).
- Hypoxic boundary corresponds to alveolar pAO₂ of 10.3 kPa (77 mm Hg or 1.5 psia) for which "acclimation can be nearly complete" according to Waligora (1993).
- Assume more conservative "textbook" conditions.



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Decompression Sickness (DCS)



- *Decompression sickness takes place when the inert gas (generally nitrogen) that normally is dissolved in body tissues at one pressure forms a gas phase ("bubbles") at a lower ambient pressure, when the the tissues become supersaturated with nitrogen. [Powell, et al. (1993)]*
 - Important consideration for mixed cabin atmospheres when extravehicular activities (EVA) are performed in lower-pressure space suits, and when changes in cabin pressure can occur as a result of planned activities and emergencies.
 - DCS symptoms can include pain ("bends"), chokes, skin manifestations, circulatory collapse, and neurological disorders (NASA (1995)).
 - DCS can be prevented or minimized by prebreathing 100% oxygen to wash out nitrogen from body tissues prior to depressurization.

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R-Value and DCS

- DCS occurrence and severity depend on the ratio, R , of the partial pressure of inert gas in equilibrium with body tissue to the final ambient pressure.
- R is known as the tissue ratio or bends ratio, frequently referred to a tissue with a 360-minute time constant for change in the inert gas content to half way between the initial and final equilibrium states.

$$R = \frac{\text{Tissue } p_{N_2}}{\text{Final Ambient (Suit) Pressure}}$$

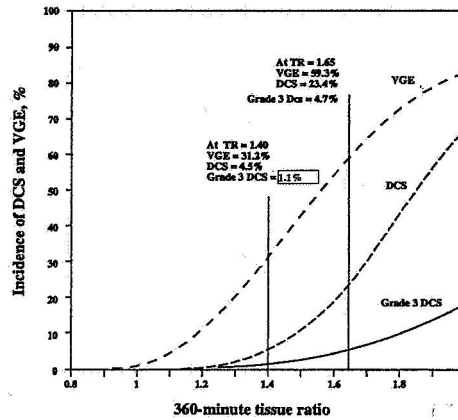


Figure Source: Horrigan, et al. (1993)
VGE = venous gas emboli

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Other DCS Factors

- DCS also depends on the duration at reduced pressure, and degree of physical activity and ambulation at reduced pressure (Conkin, et al. (1996), Conkin and Powell (2001)).
- Test data suggest that at the same R value, a higher space suit pressure will result in a lower probability of DCS (Conkin, et al. (1996)).

Figure Source: Conkin, et al. (1996).
P(DCS) = calculated probability of DCS from statistical model
P2 = final ambient (suit) pressure, psia
 $R = 1.65$

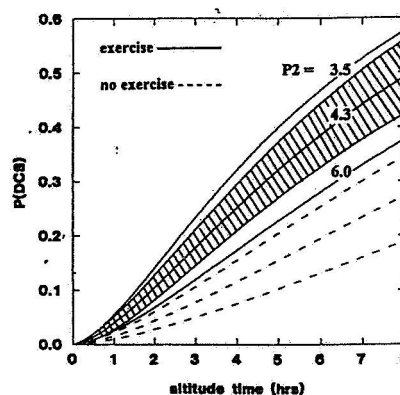


Fig. 3. The P(DCS) at either 3.5, 4.3, or 6.0 psia with (solid line) or without (dashed line) exercise at a particular time after decompression. The ratio of $P1_{N_2}$ to $P2$ (TR) in Eq. 5 was 1.65 for each curve, but notice the P(DCS) increases as $P2$ decreases at any particular time after decompression. The 95% confidence interval is provided for the curve specific to the 4.3 psia exposure that included exercise.

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Prebreathe Bounds for Surface Exploration EVAs

- DCS risks and the acceptable level of DCS risk for surface-exploration EVAs from mixed cabin atmospheres have not been established.
 - Higher physical loads imposed by partial gravity suggest higher DCS risk than in microgravity.
 - DCS symptoms must be treated locally without the option for a quick return to Earth.
 - A final R -value of 1.3-1.4 has been suggested by Conkin (2004) as a reasonable starting point based on current knowledge.
- Minimizing the prebreathe time is highly desirable in missions with frequent EVAs to maximize crew productivity.
 - An operational prebreathe of approximately 20 minutes is expected during space suit purge and checkout procedures.
 - A longer minimum prebreathe (up to 1 hour) may be required to denitrogenate the brain and spinal cord to guard against serious (Type II) DCS symptoms (Gernhardt (2004)).
 - A prebreathe time of 1 hour is assumed as a tentative upper bound for surface exploration EVAs.

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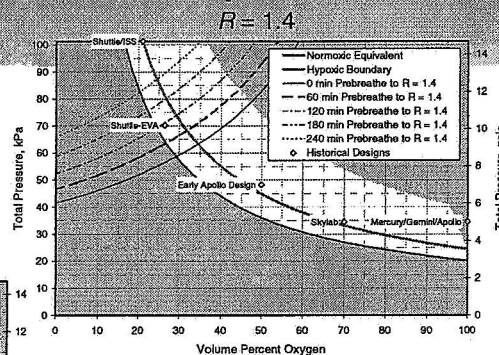
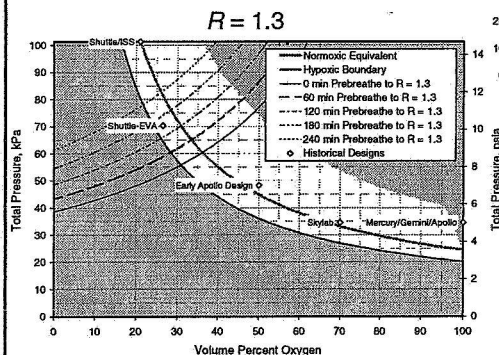
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Prebreathe Bounds for Surface Exploration EVAs

Current Space Suit Pressure

29.6 kPa (4.3 psia) Space Suit



Note: Calculated prebreathe times assume an exponential-decay tissue half-time of 360 minutes (see Conkin, et al. (1987)).

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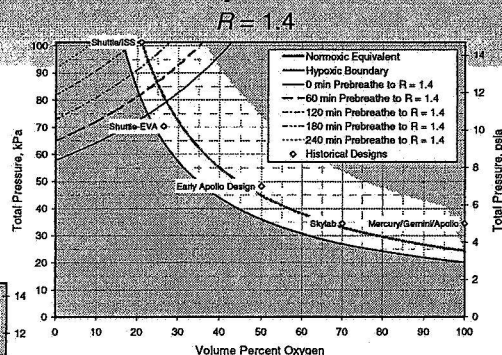
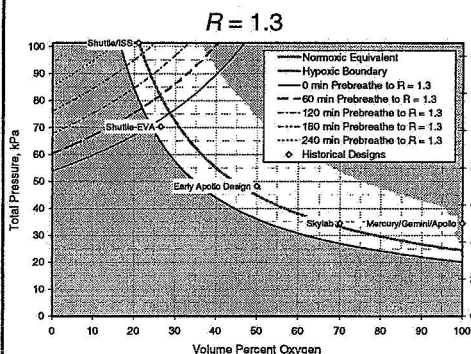
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Prebreathe Bounds for Surface Exploration EVAs

Higher Space Suit Pressure

41.4 kPa (6 psia) Space Suit



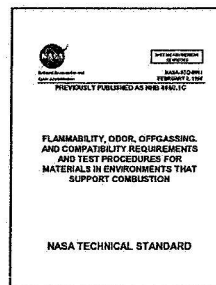
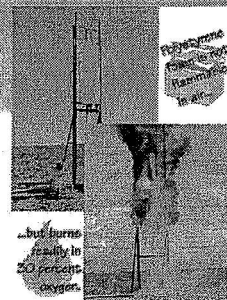
Note: Calculated prebreathe times assume an exponential-decay tissue half-time of 360 minutes (see Conkin, et al. (1987)).

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Materials Flammability

- Materials flammability is strongly dependent on oxygen concentration (volume percent) and to a lesser extent on total pressure.
 - Increasing oxygen concentration at constant atmosphere pressure decreases the minimum ignition energy, increases the flame spread rate, and increases the amount of extinguishant required to put out a fire (NFPA (2004), Beeson, et al. (1997)).
- Many non-metallic polymeric materials are flammable at 21% oxygen. The number of non-metallic materials that pass NASA flammability tests falls off rapidly as the oxygen concentration is increased.
- High oxygen concentrations, such as employed in the Skylab program (70%), would require extensive use of metallic materials.



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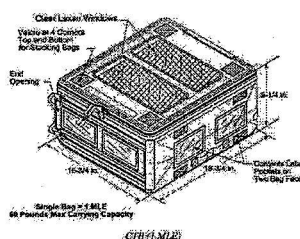
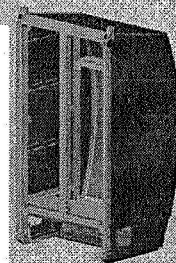
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Oxygen Indexes of Selected Nonmetallic Materials

Material	Oxygen Index	Example Applications
Cotton (cellulose)	19-27	Clothing
Epoxy	18-49	Composite Structures and Potting Compounds
Nomex (aromatic polyamide)	27-28	Soft Stowage Bags and Covers for Flammable Materials
Polyethylene	17-30	Radiation Shielding
Lexan (polycarbonate)	21-44	Housings, Windows
Teflon (polytetrafluoroethylene)	95	Wire Insulation, Tubes and Hoses

*Source: Hilado (1998). Includes flame-retardant and filled formulations.

Oxygen Index: Minimum oxygen concentration that sustains candle-like combustion (see ASTM D 2863-97 (ASTM (1997))).



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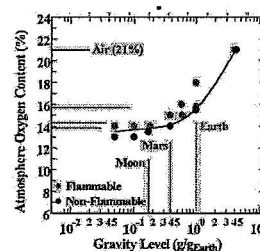
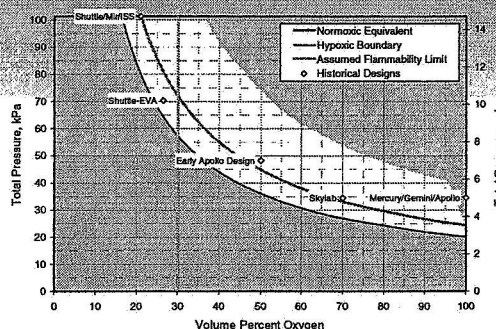
Materials Selection for Future Space Missions

- Research in deep-space ionizing radiation has found that metals are much poorer than hydrogen-containing materials in shielding the crew from high-energy particles associated with Solar Particle Events (SPE) and Galactic Cosmic Radiation (GCR):
 - *Aluminum has been found to be a poor shield material when dose equivalent is used with exposure limits for low Earth orbit (LEO) as a guide for shield requirements. Because the radiation issues are cost related—the parasitic shield mass has high launch costs—the use of aluminum as a basic construction material is clearly not cost-effective and alternate materials need to be developed.* [Wilson, et al. (1997)]
 - *Shielding against the radiation environment involves the entire spacecraft, meaning that apparently simple design choices (e.g., aluminum structures as opposed to polymer composites) can have adverse effects on radiation exposures. Shielding during every aspect of the mission is necessary to ensure crew safety, health, and performance.* [Allen, et al. (2003)]
- Composite materials have been assumed in exploration mission design studies to reduce structural mass (Drake (1998)).

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Flammability Bound

- A tentative upper bound of 30% oxygen is assumed based on the expected increased use of non-metallic materials for future missions to reduce mass and optimize radiation shielding.
- Risk analyses may result in a lower bound.
 - During Space Station Freedom design studies, a proposed increase in atmosphere oxygen concentration to 30% was strongly opposed based on both safety and microgravity-science considerations (Ruff (2004)).
 - Research suggests that the oxygen index may be lower in partial gravity than in either normal gravity or quiescent microgravity (see figure to right) (Chiaramonte (2004)).



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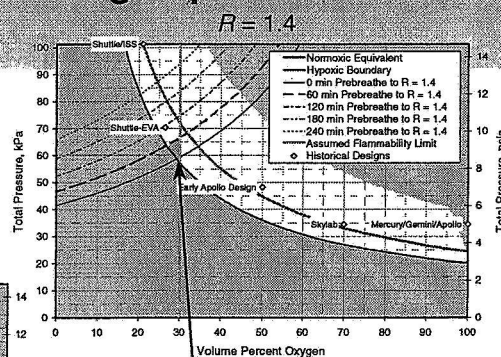
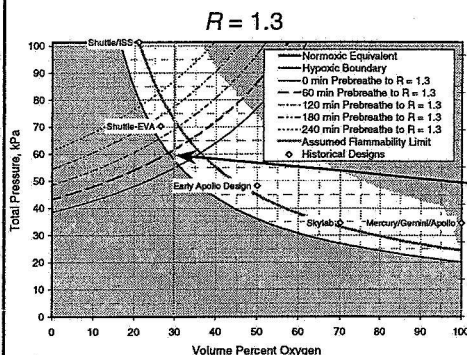
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Combined Results and Design Space

Current Space Suit Pressure

29.6 kPa (4.3 psia) Space Suit



Cabin Atmosphere Design Space

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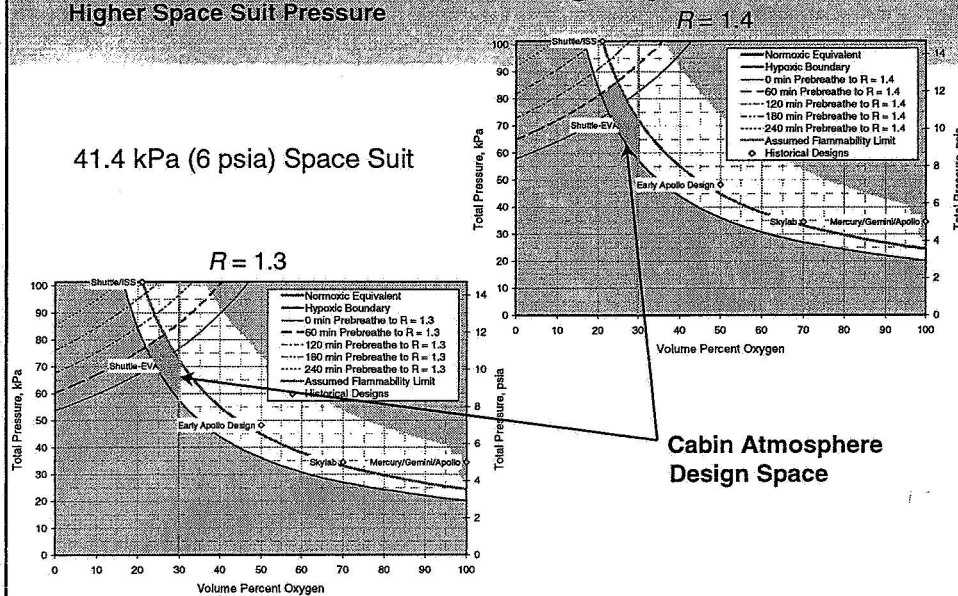
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Combined Results and Design Space

Higher Space Suit Pressure

41.4 kPa (6 psia) Space Suit



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Conclusions

- Based on the established working bounds, a small atmosphere design space is available for the current space suit pressure of 29.6 kPa (4.3 psia).
 - The design space exceeds the current Space Shuttle pre-EVA nominal oxygen concentration of 26.5% and may require recertification of materials above 30% depending on control ranges.
- A lower cabin oxygen concentration can be achieved by one or more of the following approaches:
 - Increasing the space suit pressure.
 - Accepting a higher final R -value and the associated DCS risk.
 - Accepting a longer prebreathe time.
 - Allowing a more hypoxic atmosphere.
- For transit vehicles with few EVAs, a longer prebreathe time may be acceptable.
- For vehicles that dock with the International Space Station, the ISS atmosphere conditions must be included in the design space.

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Summary

- The design of *in part* habitat atmospheres for future space missions is heavily driven by physiological and safety requirements.
- Lower EVA prebreathe time and reduced risk of decompression sickness must be balanced against the increased risk of fire and higher cost and mass of materials associated with higher oxygen concentrations.
- Any proposed increase in space suit pressure must consider impacts on space suit mass and mobility.
- Future spacecraft designs will likely incorporate more composite and polymeric materials both to reduce structural mass and to optimize crew radiation protection.
- Narrowed atmosphere design spaces have been identified that can be used as starting points for more detailed design studies and risk assessments.

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Implications for Research

- **Physiology:**
 - Further define the acceptable risk due to DCS and the acceptable risk due to hypoxia in the spacecraft environment.
- **EVA/Human Factors Engineering:**
 - Define the acceptable level of impact to EVA crew productivity due to both suit mobility and prebreathe constraints.
- **Radiation Shielding:**
 - Further define the best materials for shielding internal to the spacecraft.
- **Fire Prevention and Suppression:**
 - Further define the acceptable risks due to materials flammability and fire suppression methods.
- **Systems Integration:**
 - Perform detailed trade studies to balance safety risks against impacts to EVA mission productivity.

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- Page 3: NASA (AS16-113-18339, Apollo 16)
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- Page 15: <http://www.wstf.nasa.gov/Oxygen/ConstructionMaterials.htm>
- Page 15: NASA (NASA-STD-6001, document cover)
- Page 16: NASA (International Standard Payload Rack and Crew Transfer Bag)

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